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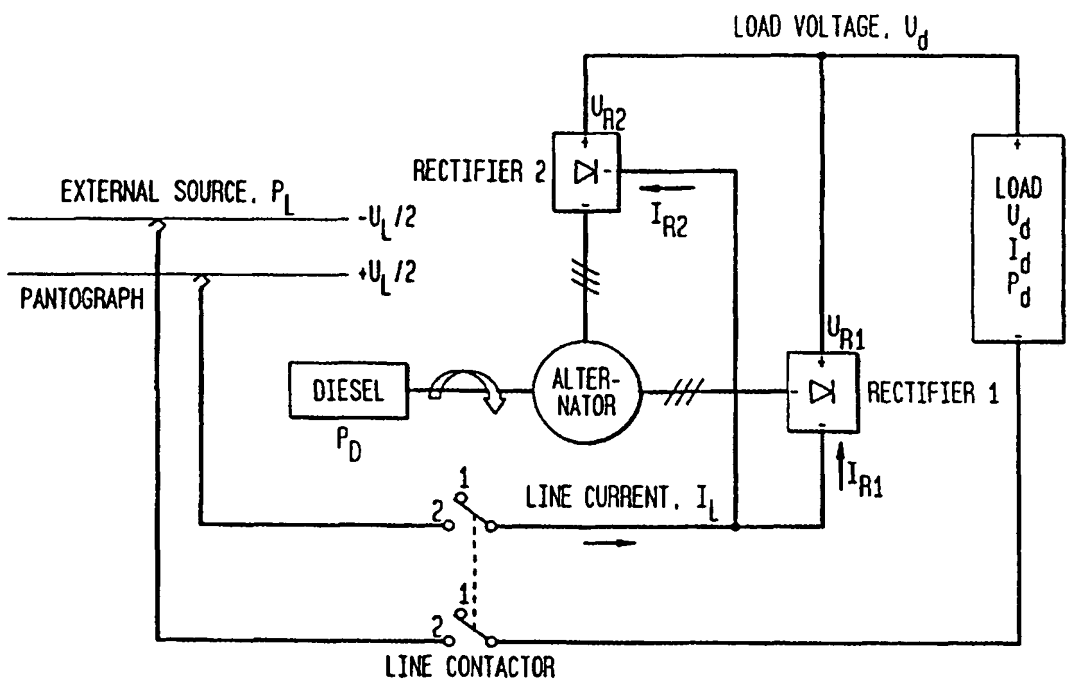

(57) Abstract

A circuit connects a low-voltage high-current DC power source (P_L) in series with a high-voltage low-current DC source (P_D). The series connection is made under full power by using the second source P_L to commutate the load current and allow the first source P_D to be reconfigured from series to parallel operation, doubling its current rating.

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SYSTEM, METHOD AND APPARATUS FOR CONNECTING ELECTRICAL SOURCES IN SERIES UNDER FULL LOAD

BACKGROUND

Field of the Invention

The present invention is related to a system, method and apparatus for connecting a low-voltage high-current DC source (P_L) when additional power is required by the load. The invention enables the series connection to be made under full power and, in a preferred embodiment, doubles the current rating of the first source P_D.

In the preferred embodiment, the invention doubles the current rating of the low-current high-voltage source P_D by breaking it into two series sources and reconfiguring them to operate in parallel. The output voltage of P_D in parallel mode is only half its series value but this is compensated for by the addition of the series connected high-current low-voltage source P_L. An important feature of this invention is that it enables the second source P_L to be connected in series with the first source P_D while under full power seamlessly and without appreciably dropping the flow of power to the load or raising the voltage of the load while operating within the rating constraints of the first and second sources P_D, P_L such that the power transfer is transparent to the load, i.e., no anamolies in power (current or voltage interruptions, spikes, oscillations, drop-off, perturbations, etc.) are sensed by the load. This is achieved by using the second source P_L to commutate the load current. The resulting circuit topology allows the load current to be increased to its limit with both sources contributing power at their rated limits. A further feature of this invention is the control strategy used to control the source P_L and effect the transitions between modes.

The Problem Solved by this Invention

In a typical application of the present invention, an electrical load is supplied by a diesel engine driving a three phase, single-winding alternator connected to a diode rectifier. The alternator/rectifier combination is constrained by current and voltage ratings based on the rated engine power at full rpm. In this case, the load is generally operated at constant DC voltage with power varying in proportion to the DC input current. This mode of operation is herein referred to as Diesel Operation (Figure 1).

It is desirable to operate the load at higher power by connecting a second high-current power source in series with the output of the rectifier. The second source, which is constrained at about half the rated load voltage, must be switched in while the load is operating at full diesel power and, furthermore, must not raise the load voltage.

The problem, therefore, is to find an economically viable circuit topology and control strategy to connect a low-voltage high-current power source P_L in series with a high-voltage low-current power source P_D that is operating an electrical load. The circuit must double the current rating of P_D, not increase the load voltage, and allow for smooth connection of the second source P_L at times when increased load current is required for higher power operation.

Approaches to Supply More Current to the Load at Rated Voltage

Additional current is available to operate the load at higher power if an external DC source is connected in parallel with the output of the rectifier (Figure 2). When the voltage of the external source is greater than the output of the rectifier, the rectifier diodes become reverse biased, the load current transfers from the alternator to the external source and, as a result, the alternator/rectifier current decreases to zero. This type of Parallel Line Connection allows an external source to supply the additional current and power at the rated voltage of the load. The connection can be made while the

load is operating at full diesel power but the voltage of the external source must equal the required voltage of the load.

If the voltage of the external source is lower than the rated load voltage, the source can be connected in series with the rectifier to provide additional power while maintaining the required load voltage (Figure 3). In this type of series line connection, the alternator is operated at a reduced voltage so that the resulting load voltage remains at its rated valued. The rectifier and external source each carry the full load current but they contribute power proportional to their respective voltages. This mode is also referred to herein as Diesel Boost Operation since the voltage of the external power source is boosted by the diesel/alternator/rectifier combination to supply the load at its rated voltage and with higher power.

Disadvantages of these Approaches

The use of a parallel line connection is limited to cases where the voltage of the external source is equal to the required operating voltage of the load.

The use of a series line connection has two serious problems. The first is that the alternator and rectifier must be oversized to handle the increased load current even though they operate at less than rated voltage while in series mode. For example, if the load power is doubled during Diesel Boost Operation and the external source supplies half the load voltage, then the alternator and rectifier must carry twice their rated current at half their rated voltage. While the alternator's output power remains essentially the same as in Diesel Mode, the losses due to the high currents are prohibitive and this mode of operation is only possible for a very short time.

The second problem is that there is considerable difficulty in switching from Diesel Operation to Series Line Operation without shutting off (i.e., interrupting) power to the load. The required load transfer must be rapid and

power. There is no economical method to accomplish the required commutation process with a simple series line connection.

An approach to supply more current to the load may be to reconfigure the alternator windings into two parallel sets of windings (forming a dual winding alternator) and connecting the windings to two rectifiers. However, there are no known means heretofore to simultaneously maintain the load at its rated voltage (without drop off, perturbations, etc.) with two parallel connected rectifiers.

In summary, a parallel line connection will not work when the voltage of the available external source is less than the rated voltage of the load. A series line connection is not practical because the size of the alternator and rectifier have to be increased to handle the higher currents and there is no feasible way to make the connection while under power. A dual winding alternator with two parallel connected rectifiers will not work because the output voltage is too low for the load.

Heretofore, there has been no means for resolving the foregoing problems.

SUMMARY AND OBJECTS OF THE INVENTION

The present invention overcomes the drawbacks mentioned above by providing a low-voltage/high-current source P_L to supply additional power to a high voltage load without appreciably dropping the flow of power to the load or raising the voltage of the load while operating within the rating constraints of the first and second sources P_D, P_L such that the power transfer is seamless, i.e., transparent to the load, i.e., no anamolies in power (current or voltage interruptions, spikes, oscillations, drop-off, perturbations, etc.) are sensed by the load.

In one embodiment, the invention doubles the current rating of a high-voltage low-current source P_D, allowing it to operate virtually indefinitely (i.e.,

extended periods of time) at increased currents required by a series connection with a low-voltage high-current source P_L.

The present invention further provides the second source P_L to be connected (and disconnected) in series with the first source P_D while the load is operating under full power.

The resulting circuit topology and control strategy overcomes the disadvantages of both the parallel and series line connections that previously rendered them unsuitable for this application. This invention makes it possible to add a high-current source in series with an operating low-current source and increase the load current to its limit.

BRIEF DESCRIPTION OF THE PREFERRED EMBODIMENT

Fig. 1 shows the diesel operation;

Fig. 2 shows the parallel line connection;

Fig. 3 shows the simple series line connection;

Fig. 4 shows the series line connection with parallel rectifiers;

Fig. 5 shows the present invention capable of full load power transfer;

Fig. 6 shows the present invention optimized for fewer components;

Fig. 7 shows the present invention in dual mode;

Fig. 8 shows the flow chart for the connect sequence of the present invention;

Fig. 9 shows the flow chart for the disconnect sequence the present invention; and

Fig. 10 shows the diesel powered AC haul truck with the dual mode diesel boost trolley configuration or the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention is preferably explained by considering the solution in two parts. However, it will be appreciated that the form of explanation shall not limit the scope of the invention as claimed and that the invention may be explained or practiced otherwise.

Part I – Use of a Dual Winding Alternator and a Second Rectifier to Double the Current Rating

The solution to the problem of high alternator/rectifier currents during series operation is to use a dual winding alternator and two rectifiers as illustrated in Figure 4. In this instance, the alternator is configured with two star windings and the resulting six outputs are connected to two separate diode rectifiers. In the preferred embodiment, each winding has the same rated current and one-half the rated voltage as the single winding alternator. Of course, other configurations are possible in the present invention. For example, it is possible to configure three star windings with nine outputs connected to three separate rectifiers.

The outputs of the two rectifiers can be connected in series to supply the rated current and voltage to the load. The addition of the second rectifier is not obvious because the additional rectifier slightly reduces the overall system efficiency, but this is acceptable especially for the particular application of the present invention. An advantage revealed by the present invention is that with the use of each additional rectifier the voltage rating of each rectifier may be reduced because the series connection reduces the blocking voltage requirement on each rectifier.

This series configuration, for example, is suitable for normal Diesel Operation when the load power can be met by the diesel engine and the full

load voltage must be supplied by the alternator/rectifier combination. In this mode, the alternator windings and rectifier are at the same current levels that they would be for a single winding/single rectifier solution. Advantageously, the voltage and flux levels in the alternator are unchanged.

The outputs of the two rectifiers can be connected in parallel to supply, in the preferred embodiment, twice the rated current at half the rated voltage. This configuration is suitable for Diesel Boost Operation when the alternator and rectifier must handle much higher currents at a greatly reduced voltage. Here again, the alternator windings and rectifiers operate at the same current level as for the single winding case, but in this case, the parallel configuration doubles the output current.

The use of a dual winding alternator with two rectifiers that can be connected in either series or parallel solves the problem of excessively high alternator and rectifier currents. The series connection provides rated voltage under Diesel Operation and the parallel connection doubles the output current capability. Hence, the present invention resolves the previous problems seamlessly and without appreciably dropping the flow of power to the load or raising the voltage of the load while operating within the rating constraints of the first and second sources P_D, P_L such that the power transfer is transparent to the load, i.e., no anamolies in power (current or voltage interruptions, spikes, oscillations, drop-off, perturbations, etc.) are sensed by the load.

The use of a dual winding alternator with two rectifiers that can be configured in either series or parallel may be applied to various applications. Although the present invention is explained below with reference to a diesel engine trolley, the invention may be applied, for example, to locomotives where the available power is limited, high current is required at low voltage, and high voltage is required at low current, corresponding to low speed and high speed operation, respectively. A distinguishing feature of this invention is that the dual winding alternator with two rectifiers is used to facilitate smooth series-to-parallel and parallel-to-series transitions particularly while under full load and while maintaining full load voltage.

In the preferred embodiment, a voltage source inverter (VSI) is used as the load to facilitate this smooth transition. The VSI incorporates a capacitor bank as part of its input circuit, which forms the so-called DC link. The VSI can be operated so that, within certain limits, its output voltage (which is connected to the load) can be adjusted independently of the DC link (input) voltage. The system controller adjusts the DC link voltage by varying the excitation of the alternator.

Part 2 – Use an External (Low Voltage) Source to Commutate the Load

The solution to the commutation problem is to make the transition in distinct steps using a new circuit topology and control strategy. In the circuit shown in Figure 5, the external power source is first connected in parallel with one of the dual rectifiers. This provides a commutation path for the load current so that the said rectifier can be disconnected and then reconnected in parallel with the other rectifier. This smoothly reconfigures the alternator and rectifiers from series to parallel operation, doubles their combined current rating, and halves their voltage rating, without interrupting the load current. Finally, the load current is increased to its limit with both sources contributing power at their rated limits.

Connect Sequence: Making the External Series Connection Under Load

The commutation process to connect the external source in series and switch the rectifier outputs from series to parallel configuration is a process comprising at least the following steps set forth in Figure 8. In the preferred embodiment, the controller controls the operation.

In summary, the connection sequence of the preferred embodiment begins with the rectifiers of the dual-windings of a source in a series configuration. The external source is placed in a parallel configuration with one of the rectifiers and the internal source gradually decreases in voltage until this rectifier is reverse biased, i.e., no longer supplying power to the load.

The reversed biased rectifier is then placed in parallel with the other rectifier in order to provide twice the current as the original configuration.

Step 802 begins from an initial state of Diesel Operation with the rectifier outputs connected in series and the load supplied by the diesel engine (Step 804). During Diesel Operation, the alternator excitation and engine speed are controlled by the controller (CPU, Figure 4) so as to meet the power, voltage, and current requirements of the load. For diesel boost operation, the system controller (also referred to as the TCU (Traction Control Unit)) controls the switching in Figure 4-6 on the basis of input signals such as the external line voltage and vehicle speed. The TCU controls an automated sequence to connect and disconnect the external power source while under full load.

The transition begins by measuring the external line voltage (Step 806) and adjusting the alternator excitation (Step 808) so that the rectified outputs of each winding are close to the external line voltage (U_L). The line contactor is then closed (Step 810) to connect the external source in parallel with the output of Rectifier 1. No precharging is required before making the connection because the system controller maintains the rectifier output voltage to be close to (U_L) the external line voltage and no appreciable current flows through the line contactor.

Next, the excitation is reduced slightly (Step 812) to lower the DC output of the rectifiers and therefore lower the input voltage of the inverter's DC link. As a result, the external supply reverse biases Rectifier 1 and causes the portion of the load carried by Rectifier 1 to be transferred to the external supply. The load current is now supplied by the external source in series with Rectifier 2. No current flows in Rectifier 1. Opening switch S_2 (Step 814) now opens the series connection between the two rectifiers at zero current. Due to this arrangement, the load is maintained at all times at the voltage and current level corresponding to its rated power during Diesel Operation (P_D).

It will be appreciated that this circuit topology is able to advantageously connect the line without any precharge process and then open switch S_2 at zero current because the load is a voltage source inverter. The controller for such an inverter is able to compensate, within certain limits, for variations in the input voltage connected to the inverter's DC link and maintain the load at full power. Therefore, in addition to its normal function of controlling the load inverter, the controller also actively adjusts the excitation to vary (Step 816) the inverter input voltage during the connection sequence to provide a smooth transition to series operation while under load. This results in a seamless series connection to the external source.

At this time, the series connection between Rectifier 1 and Rectifier 2 is open and has no effect on the operation because there is no current flowing in Rectifier 1. The negative output of Rectifier 1 is then disconnected (Step 818) from the negative terminals of the DC bus and reconnected to the negative output of Rectifier 2. Here again, no current flows in Rectifier 1 or either switch due to the circuit topology.

Step 822 is to connect Rectifier 1 in parallel with Rectifier 2 by connecting positive output of Rectifier 1 to the positive output of Rectifier 2. Since the alternator windings share a common flux path, half of the load current flowing in winding 1 quickly and smoothly transfers to winding 2 until both windings and rectifiers equally share the load, thereby completing the transfer.

The outputs of the two rectifiers are now connected in parallel with each other and in series with the external source. Each alternator winding operates at its full rated voltage but only half its rated current. The diesel operates at half its rated output (0.5^*P_D) and the external supply provides the rest of the power (0.5^*P_L). The load operates at its rated voltage and with current and power equivalent to what the diesel engine alone provides during Diesel Operation.

The next Step (824) is to increase the load power to its maximum by increasing the load current. The current splits equally between the two rectifiers and alternator windings so they are not overloaded. The increased power comes partially from the diesel and partially from the external source. The transition from full diesel power (P_D) to full load power ($P_F=P_D+P_L$) occurs at the same voltage by doubling the current drawn from the line and through the alternator. This power increase is also a seamless transition in that load voltage remains constant and the controller simply adjusts the load to draw more current from the combined power sources.

After the rectifiers are connected in parallel, the controller adjusts the alternator excitation so as to maintain the load at the most optimum voltage. This voltage could be adjusted, for example, in consideration of the vehicle's speed to maintain the load at its most desirable operating point. The controller can also compensate for variations in line voltage by adjusting the excitation and so maintain the load at its ideal operating point.

Disconnect Sequence: Removing the External Series Connection Under Load

The commutation process to disconnect the external power source and restore the series connection of the two rectifier outputs for Diesel Operation will be described with reference to Figure 9.

In Step 902 the controller seamlessly reduces the load current to a level that can be supplied by the diesel engine (P_D). Step 904 is to disconnect the positive output of Rectifier 1 from the positive output of Rectifier 2. This removes the parallel rectifier connection and the load current smoothly transfers completely to the remaining winding. The engine, alternator and rectifier still provide half the load power, but one half of the alternator and one rectifier are at full current and voltage and the other half have no current. The other half of the load voltage is supplied in this instance by the line. Step 906 is to disconnect the negative output of Rectifier 1 from the negative output of Rectifier 2 and reconnect the negative output of Rectifier 1 to the negative terminal of the DC bus (Step 908).

In preparation (Step 910) for restoring the serial connection between the two rectifier outputs, the controller adjusts the excitation to ensure that the rectifier output is slightly less than the line voltage. The positive output of Rectifier 1 is then reconnected in Step 912 to the negative output of Rectifier 2. No current flows during or after this transition because the line voltage reverse biases Rectifier 1. The controller in Step 917 then raises the excitation until Rectifier 1 begins to conduct and the diesel picks up the second half of the load, reducing the line current to zero, seamlessly transferring the load to the diesel. The line contactor is now opened at zero current (Step 916). This leaves the system back in Diesel Operation with (diesel) rated current and voltage at the load.

In the preferred embodiment, the two switches used to reconfigure the system for Diesel Boost Trolley Operation are single pole (not three phase) and are not required to make or break large currents or voltages. They generally operate at zero current.

The precharge circuit in the embodiment shown in Figure 5 controls the rate of power transfer from the alternator and Rectifier 1 to the external source. This simplifies the control problem and allows the system controller to maintain the rated load voltage during the transfer. The rating of the precharge circuit may be minimized because it only needs to accommodate the difference in voltage between the external source voltage and the output of Rectifier 1 at the beginning of the transfer. In some embodiments of the invention (Figure 6), the precharge circuit can be eliminated by means of a proper control strategy implemented by the controller.

The circuit of the present invention advantageously allows a high-current, high-voltage load to be supplied with supplemental power from an existing high-current, low-voltage source. Further, the circuit allows the load to operate at power levels beyond what available diesel engines can provide. In addition, the circuit topology minimizes the size of the alternator by permitting parallel connection of the windings (through the rectifiers) to

effectively double its rated current when only half its rated voltage is required. The present invention provides a smooth and bumpless transfer, allowing the load to operate at maximum diesel power throughout the transition seamlessly and without appreciably dropping the flow of power to the load or raising the voltage of the load while operating within the rating constraints of the first and second sources P_D, P_L such that the power transfer is transparent to the load, i.e., no anamolies in power (current or voltage interruptions, spikes, oscillations, drop-off, perturbations, etc.) are sensed by the load.

The present invention shall now be described as a particular example. However, it shall be clear that the invention is not limited to such example and may, in addition, be practiced otherwise. The following notations will be used in the following example.

Notation:	Subscripts:
U = Voltage	$_L$ = Line (L=Trolley Line)
I = Current	$_D$ = Diesel
P = Power	$_d$ = Load Value (d=DC)
	$_R$ = Rectifier

A diesel powered off-highway haul truck (Figure 10) is driven by two AC electric traction motors supplied by two inverters in accordance with the circuit topology shown in Figure 4. The inverters are capable of handling a combined power P_d at DC input voltage U_d and DC input current I_d. The inverters are connected to a common DC bus and are fed by an alternator and rectifier bridge at the rated inverter input voltage U_d. At this voltage level the alternator and rectifier can supply current I_D, where I_D is only approximately half of I_d. The alternator is driven by a diesel engine capable of delivering maximum power P_D, where P_D is approximately half of the load power P_d.

While travelling up a grade, it is desired to ascent the grade at a faster rate. To that end, the vehicle is connected to a low voltage trolley line with voltage U_L by means of a pantograph, thereby increasing the DC current supplied to the inverters from I_D to I_L. This must be done under the environment of maintaining the inverters at their rated DC input voltage U_d. This provides approximately twice the power to the load and thereby doubles the vehicle speed while on grade when connected to the low voltage trolley line.

The Parallel Line Connection of the trolley line with the DC bus is not possible since the voltage required by the inverters U_d is almost twice the available trolley voltage U_L. A Series Line Connection to the trolley line is not possible since the available trolley current I_L is twice the rated DC current of the alternator and rectifier I_D and they will rapidly overheat.

The truck is able to drive from the loading shovel to the trolley line under diesel power P_D and can go up the grade at this power level. To utilize the additional power available from the trolley, the truck must be able to connect to the trolley line while maintaining continuous operation on the grade at power P_D. If the power level falls during the transition, the truck will slow below the minimum allowable trolley speed limit (a safety limitation for mine personnel) and be forced stop.

Prior to this invention, it has not been possible for the high voltage inverters to make use of the available low voltage trolley power. Using the circuit topology and control strategy described in the present invention it is now possible to operate the truck on a low voltage trolley in Diesel Boost Mode at the full rated load power P_d.

Diesel Boost Configuration and Control Strategy of the Present Invention

The single winding alternator and diode rectifier of Figure 1 are replaced with a dual winding alternator connected to two diode rectifiers (Figure 6). The two windings are identical and each supplies half the rated voltage of the alternator. A two-pole line contactor brings the trolley voltage to where it can be connected in parallel with Rectifier 1. A single pole, double-throw changeover switch (S_3) and two single-pole, single-throw switches (S_1 and S_2) enable the outputs of Rectifier 1 to be connected either in series or parallel with Rectifier 2. An additional single pole high-speed circuit breaker provides overcurrent protection between the truck and trolley systems.

With all the switches in position 1, the two rectifiers are in series and there is no connection to the trolley line. The load operates at $U_D=U_{d,max}$, $I_D<I_{d,max}$ and $P_D<P_{dmax}$. With all the switches in position 2, the two rectifiers

are in parallel with each other and in series with the trolley line. The load operates at $U_D=U_{d,max}$, $I_L=I_{d,max}$ and $P_D+P_L=P_{dmax}$.

The truck operates in normal Diesel mode when the switches are in position 1 and all the power is provided by the diesel engine. Transition from Diesel to Diesel Boost operation functions according to the connection sequence described previously. During Diesel Boost operation, the switches are all in position 2. Transition from Diesel Boost to Diesel operation functions according to the disconnect sequence described previously.

Of particular importance is that the duration of the actual transfer from one mode to the other is not critical because the transfer takes place with the vehicle operating under full diesel power. With no precharge interval, the limiting factor in the transition is the time required to raise and lower the pantograph. Approximately one second is required for the DC link voltage regulation to stabilize before the line contactor is closed and then the connect sequence begins. It has been found that, with the present invention, within one second after S_1 is closed the controller can raise the load power to its full level.

The transition from diesel to trolley is bumpless and the vehicle will not slow down at all during the transfer. While on trolley, the diesel power (P_D) is supplemented by power from the wayside substations (P_L) and the inverters are able to operate at their full power. Depending on the exact voltage, current and power levels involved, this approximately doubles the vehicle's on-grade speed. The transition from trolley to diesel is also quick and smooth with the present invention. Hence, the present invention resolves the previous problems seamlessly and without appreciably dropping the flow of power to the load or raising the voltage of the load while operating within the rating constraints of the first and second sources P_D, P_L such that the power transfer is transparent to the load, i.e., no anamolies in power (current or voltage interruptions, spikes, oscillations, drop-off, perturbations, etc.) are sensed by the load.

Alternative Examples of the Invention

In mines where the trolley voltage is suitably high ($U_L=U_d$) the truck can operate in Direct Trolley (DT) mode. This uses the Parallel Line Connection described with reference to Figure 2 and does not require switches S_1, S_2 or S_3, only the circuit breaker and line contactor.

There are, however, some situations where both high and low voltage trolley systems are installed, or could be installed, in the same mine. In this case, it would be desirable to operate the truck on either line using either the low voltage line in Diesel Boost Trolley (DBT) mode or the high voltage line in Direct Trolley (DT) mode. A variation of the invention, as shown in Figure 7, is the addition of a second single-pole, double-throw switch (S_4) to allow the truck to operate on both high and low voltage trolley systems.

The switch's common terminal in this case is connected to the load side of the positive pole of the line contactor. The other terminals are connected to the positive and negative sides of Rectifier 2, such that in position 1, the line contactor is connected to the negative terminal of Rectifier 2 and in position 2 the line contactor is connected to the positive terminal of Rectifier 2. With S_4 in position 1, the truck can operate in either Diesel or Diesel Boost mode by moving the other switches to position 1 or position 2, as previously described. This is suitable for operation under diesel power or on the low voltage trolley system, when $U_L<U_d$. With S_4 in position 2, and all other switches in position 1, the truck can operate in Direct Trolley mode as described above. This is suitable for operation on the high voltage trolley system, where $U_L=U_d$. In operation, the operator drives the vehicle under either trolley system and then raises the pantograph. The system controller then measures the trolley line voltage and positions S_4 accordingly. This provides safe, automatic, and reliable operation on either trolley system without any consideration from the driver as to the operating voltage of the trolley line.

I CLAIM:

1. An apparatus for seamlessly placing an additional source of additional power in series with a source while said source supplies a load with power such that , said apparatus comprising:

a first source for supplying said load with said power;

a second source for supplying said load with said additional power; and

a coupler for electrically coupling said second source seamlessly in series with said first source such that, while said first source supplies power to said load, said second source is seamlessly placed in series with said first source to significantly increase power to said load.

2. The apparatus according to claim 1, wherein said coupler seamlessly places said second source in series with said first source thereby preventing any perturbations in distribution of power between said first and second sources to be sensed by the load.

The apparatus according to claim 1, wherein said first source includes at least two series-connected circuit elements that each supply a portion of said power to said load; wherein said coupler couples said second source in parallel with at least one of said circuit elements and then uncouples said circuit element(s) from said second source thereby seamlessly placing the remaining elements of said first source in series with said second source.

3. The apparatus according to claim 1, wherein the coupler also couples said disconnected circuit element(s) of said first source in a parallel configuration with at least one of the other circuit elements of said first source.

4. The apparatus according to claim 3, further comprising a controller for controlling the first source, when at least one of said circuit elements is coupled by said coupler to said second source, to lower the output voltage of said element of first source until the one of said circuit elements is reverse biased, thereby reducing the current of the one of said circuit elements to a relatively zero current.

5. The apparatus according to claim 1, wherein said first source has a first rating constraint and said second source has a second rating

constraint, wherein when said first source supplies power to said load, said second source significantly increases power to said load without appreciably dropping flow of power to said load or raising voltage of said load while operating within said first and second rating constraints of the first and second sources, respectively, such that said power transitioned between said first source and said second source is effectively transparent to said load.

6. The apparatus according to claim 1, further comprising a controller for controlling said coupler for electrically coupling said second source to said first source.

7. The apparatus according to claim 2, wherein said controller controls said coupler to switch between a series configuration of said circuit elements which provides power from said first source to the load and a parallel configuration of said circuit elements which provides power from said first source to the load in conjunction with said second source.

8. The apparatus according to claim 3, wherein said series configuration configures a circuit element that channels power from said first source to said load in series with a shared circuit element, which is shared between said first source and said second source, that channels power from said first source to said load, and wherein said parallel configuration configures said circuit element in parallel with said shared element, which channels power from said first source in conjunction with said second source to said load.

9. The apparatus according to claim 5, wherein said shared circuit element is a first rectifier and said circuit element is a second rectifier.

10. The apparatus according to claim 6, wherein said first source is a dual-winding source, and wherein said first rectifier is coupled to a first winding of said first source and said second rectifier is coupled to a second winding of said first source.

11. The apparatus according to claim 7, wherein said coupler further comprises a switch for selectively uncoupling a positive output terminal of said first rectifier from a negative output terminal of said second rectifier, thereby breaking the series connection of said circuit elements of said first source.

12. The apparatus according to claim 7, wherein said coupler further comprises another switch for selectively uncoupling a negative output terminal of said first rectifier from the negative input terminal of load and coupling said negative output terminal to a negative output terminal of a said remaining circuit element of said first source, thereby preparing for configuring said first rectifier in said parallel configuration.

13. The apparatus according to claim 7, wherein said coupler further comprises another switch for selectively coupling said positive input terminal of said first rectifier to a positive input terminal of said second rectifier, thereby configuring said first rectifier in said parallel configuration.

14. The apparatus according to claim 2, further comprising a line contactor for selectively coupling said second source to said switch for selectively coupling said second source to said second rectifier.

15. The apparatus according to claim 2, wherein said load includes a DC link input capacitive element, wherein said controller adjusts an excitation of the first source to vary the voltage present on said DC link element independent of said second source and independent of load voltage requirements and load power requirements in order to optimize drive system performance.

16. The apparatus according to claim 2, wherein said load includes a DC link input capacitive element, wherein said controller adjusts an excitation of said first source to compensate for variations in output voltage of said second source in order to maintain optimum voltage in said DC link element.

17. The apparatus according to claim 1, wherein said load is one or more AC voltage source inverters.

18. The apparatus according to claim 17, wherein said inverters drive a diesel powered off-highway haul truck.

19. The apparatus according to claim 13, wherein said first source is an AC electric alternator.

20. The apparatus according to claim 20, wherein said first source is part of a diesel powered off-highway haul truck.

21. The apparatus according to claim 15, wherein said second source is a trolley power line external to said diesel-powered off-highway haul truck.

22. The apparatus according to claim 15, wherein said second source is a relatively lower voltage trolley power line.

23. An apparatus for seamlessly placing an additional source of additional power in series with a source while said source supplies a load with power such that , said apparatus comprising:

first means for supplying said load with said power;

second means for supplying said load with said additional power; and

coupling means for electrically coupling said second means seamlessly in series with said first means such that, while said first means supplies power to said load, said second means seamlessly placed in series with said first means to significantly increase power to said load.

24. The apparatus according to claim 24, wherein said coupler seamlessly places said second means in series with said first source thereby preventing any perturbations in distribution of power between said first and second means to be sensed by the load.

The apparatus according to claim 24, wherein said first means includes at least two series-connected circuit means that each supply a portion of said power to said load; wherein said coupler couples said second means in parallel with at least one of said circuit means and then uncouples said circuit means from said second source thereby seamlessly placing the remaining elements of said first source in series with said second source.

25. The apparatus according to claim 24, wherein the coupling means also couples said disconnected circuit means of said first means in a parallel configuration with at least one of the other circuit means of said first means.

26. The apparatus according to claim 26, further comprising a controller for controlling the first source, when at least one of said circuit means is coupled by said coupling means to said second source, to lower the output voltage of said element of first means until the one of said circuit

means is reverse biased, thereby reducing the current of the one of said circuit means to a relatively zero current.

27. The apparatus according to claim 24, wherein said first source has a first rating constraint and said second source has a second rating constraint, wherein when said first source supplies power to said load, said second source significantly increases power to said load without appreciably dropping flow of power to said load or raising voltage of said load while operating within said first and second rating constraints of the first and second sources, respectively, such that said power transitioned between said first source and said second source is effectively transparent to said load.

28. The apparatus according to claim 24, further comprising control means for controlling said coupling means for electrically coupling said second means to said first means.

29. The apparatus according to claim 25, wherein said control means controls said coupling means to switch between a series configuration of said circuit means which provides power from said first means to the load and a parallel configuration of said circuit means which provides power from said first means to the load in conjunction with said second means.

30. The apparatus according to claim 26, wherein said series configuration configures a circuit means that channels power from said first means to said load in series with shared circuit means, which is shared between said first means and said second means, that channels power from said first means to said load, and wherein said parallel configuration configures said circuit means in parallel with said shared element, which channels power from said first means in conjunction with said second means to said load.

31. The apparatus according to claim 28, wherein said shared circuit means is a first rectifier and said circuit means is a second rectifier.

32. The apparatus according to claim 29, wherein said first means is a dual-winding source, and wherein said first rectifier is coupled to a first winding of said first means and said second rectifier is coupled to a second winding of said first means.

33. The apparatus according to claim 30, wherein said coupling means further comprises a switch for selectively uncoupling a positive output terminal of said first rectifier from a negative output terminal of said second rectifier, thereby breaking the series connection of said circuit means of said first means.

34. The apparatus according to claim 30, wherein said coupling means further comprises another switch for selectively uncoupling a negative output terminal of said first rectifier from the negative input terminal of load and coupling said negative output terminal to a negative output terminal of a said remaining circuit means of said first means, thereby preparing for configuring said first rectifier in said parallel configuration.

35. The apparatus according to claim 30, wherein said coupling means further comprises another switch for selectively coupling said positive input terminal of said first rectifier to a positive input terminal of said second rectifier, thereby configuring said first rectifier in said parallel configuration.

36. The apparatus according to claim 25, further comprising a line contactor for selectively coupling said second means to said switch for selectively coupling said second means to said second rectifier.

37. The apparatus according to claim 25, wherein said load includes a DC link input capacitive element, wherein said control means adjusts an excitation of the first means to vary the voltage present on said DC link element independent of said second means and independent of load voltage requirements and load power requirements in order to optimize drive system performance.

38. The apparatus according to claim 25, wherein said load includes a DC link input capacitive element, wherein said control means adjusts an excitation of said first means to compensate for variations in output voltage of said second means in order to maintain optimum voltage in said DC link element.

39. The apparatus according to claim 24, wherein said load is one or more AC voltage source inverters.

40. The apparatus according to claim 40, wherein said inverters drive a diesel powered off-highway haul truck.

41. The apparatus according to claim 36, wherein said first means is an AC electric alternator.

42. The apparatus according to claim 43, wherein said first means is part of a diesel powered off-highway haul truck.

43. The apparatus according to claim 38, wherein said second means is a trolley power line external to said diesel-powered off-highway haul truck.

44. The apparatus according to claim 38, wherein said second means is a relatively lower voltage trolley power line.

FIG. 1

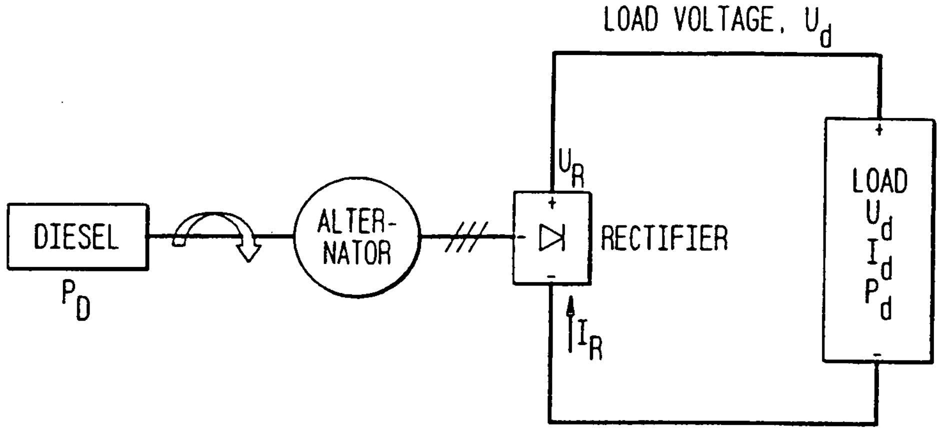

LOAD VOLTAGE, U_d
DIESEL
P_D
ALTER-NATOR
U_R
RECTIFIER
I_R
LOAD
U_d
I_d
P_d

FIG. 2

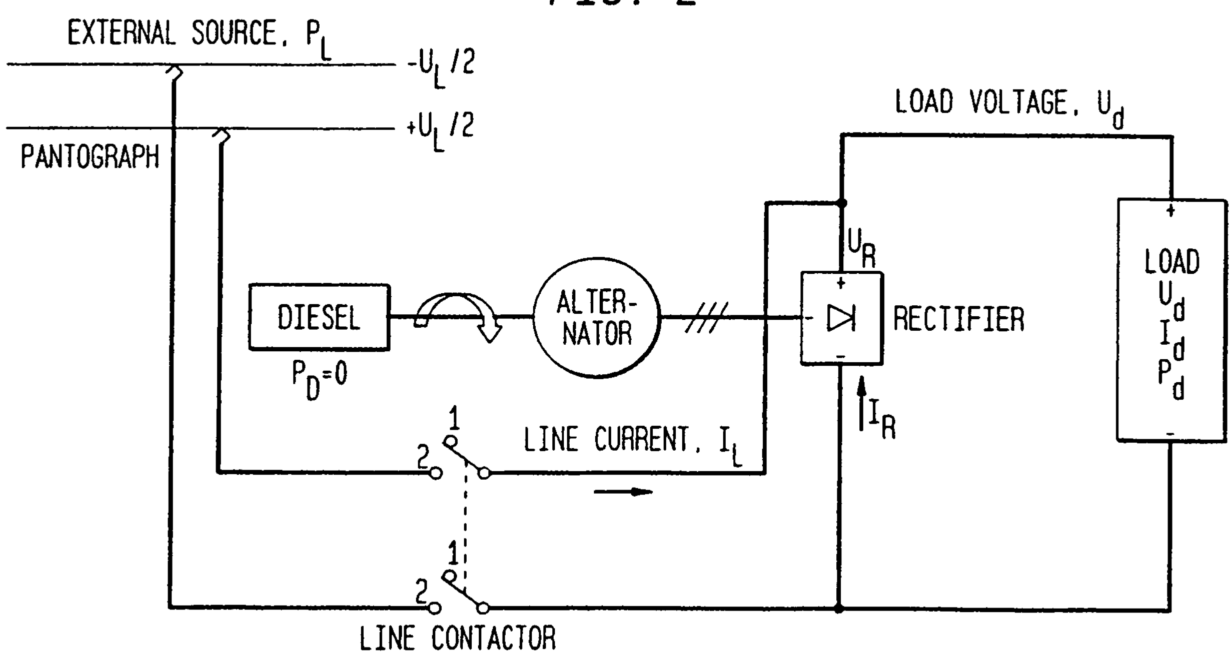

EXTERNAL SOURCE, P_L
$-U_L/2$
$+U_L/2$
PANTOGRAPH
LOAD VOLTAGE, U_d
DIESEL
$P_D=0$
ALTER-NATOR
U_R
RECTIFIER
I_R
LOAD
U_d
I_d
P_d
LINE CURRENT, I_L
1
2
1
2
LINE CONTACTOR

FIG. 3

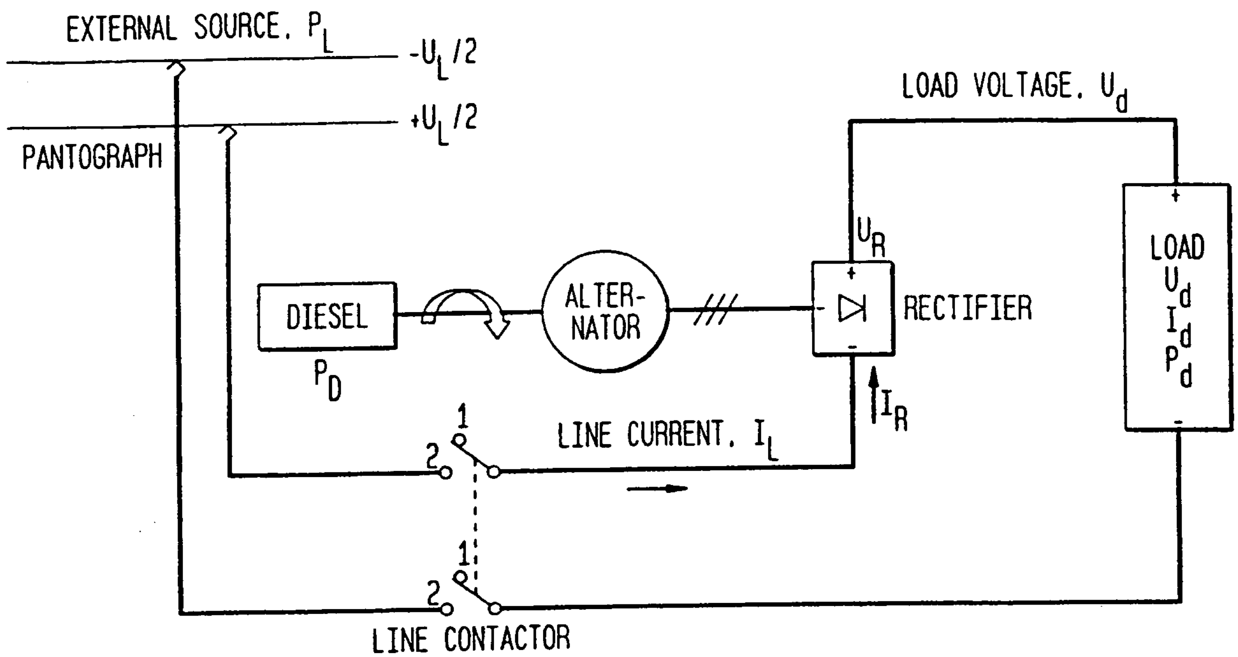

EXTERNAL SOURCE, P_L
$-U_L/2$
$+U_L/2$
PANTOGRAPH
LOAD VOLTAGE, U_d
U_R
DIESEL
P_D
ALTER-
NATOR
RECTIFIER
LOAD
U_d
I_d
P_d
I_R
1
2
LINE CURRENT, I_L
1
2
LINE CONTACTOR

FIG. 4

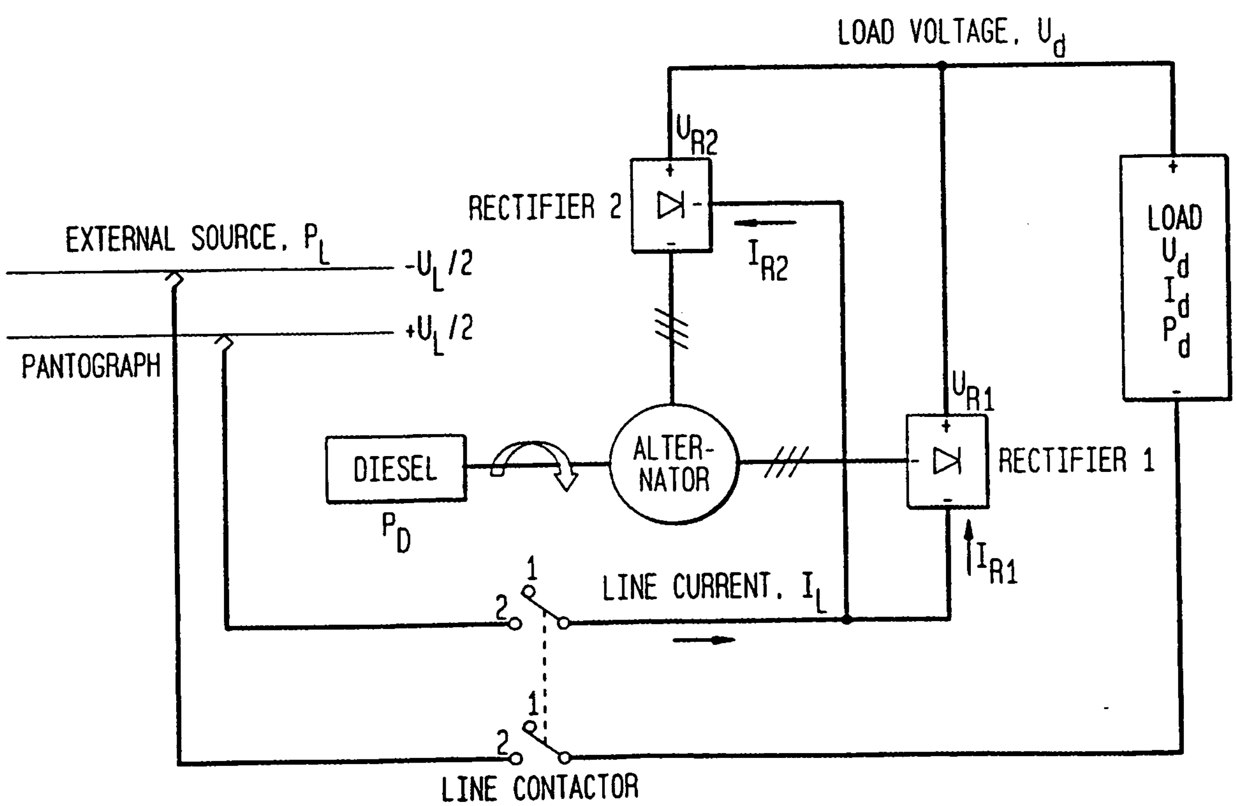

LOAD VOLTAGE, U_d
U_{R2}
RECTIFIER 2
I_{R2}
EXTERNAL SOURCE, P_L
$-U_L/2$
$+U_L/2$
PANTOGRAPH
LOAD
U_d
I_d
P_d
U_{R1}
DIESEL
P_D
ALTER-
NATOR
RECTIFIER 1
I_{R1}
1
2
LINE CURRENT, I_L
1
2
LINE CONTACTOR

FIG. 5

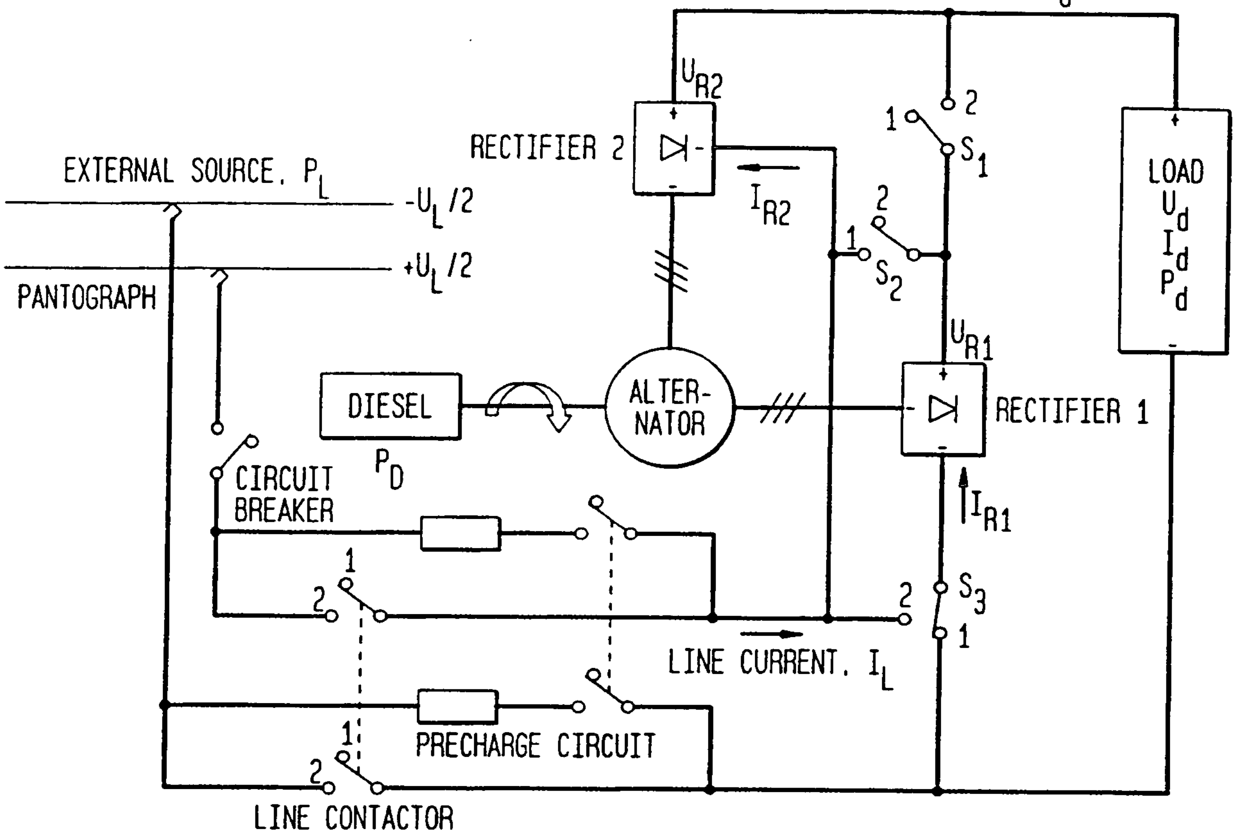

LOAD VOLTAGE, U_d
U_{R2}
RECTIFIER 2
I_{R2}
EXTERNAL SOURCE, P_L
$-U_L/2$
$+U_L/2$
PANTOGRAPH
S_1
S_2
LOAD
U_d
I_d
P_d
U_{R1}
DIESEL
ALTER-
NATOR
RECTIFIER 1
P_D
CIRCUIT
BREAKER
I_{R1}
S_3
LINE CURRENT, I_L
PRECHARGE CIRCUIT
LINE CONTACTOR

FIG. 6

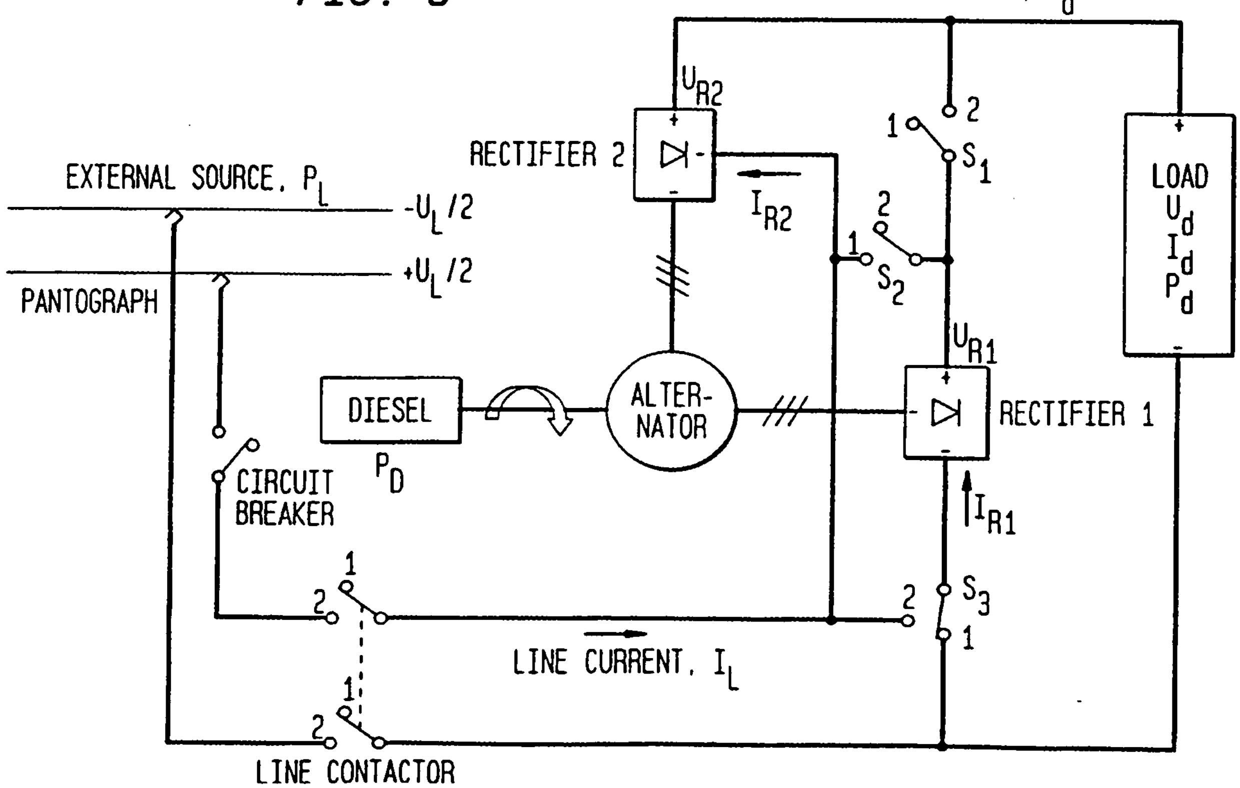

LOAD VOLTAGE, U_d
U_{R2}
RECTIFIER 2
I_{R2}
EXTERNAL SOURCE, P_L
$-U_L/2$
$+U_L/2$
PANTOGRAPH
S_1
S_2
LOAD
U_d
I_d
P_d
U_{R1}
DIESEL
ALTER-
NATOR
RECTIFIER 1
P_D
CIRCUIT
BREAKER
I_{R1}
S_3
LINE CURRENT, I_L
LINE CONTACTOR

FIG. 7

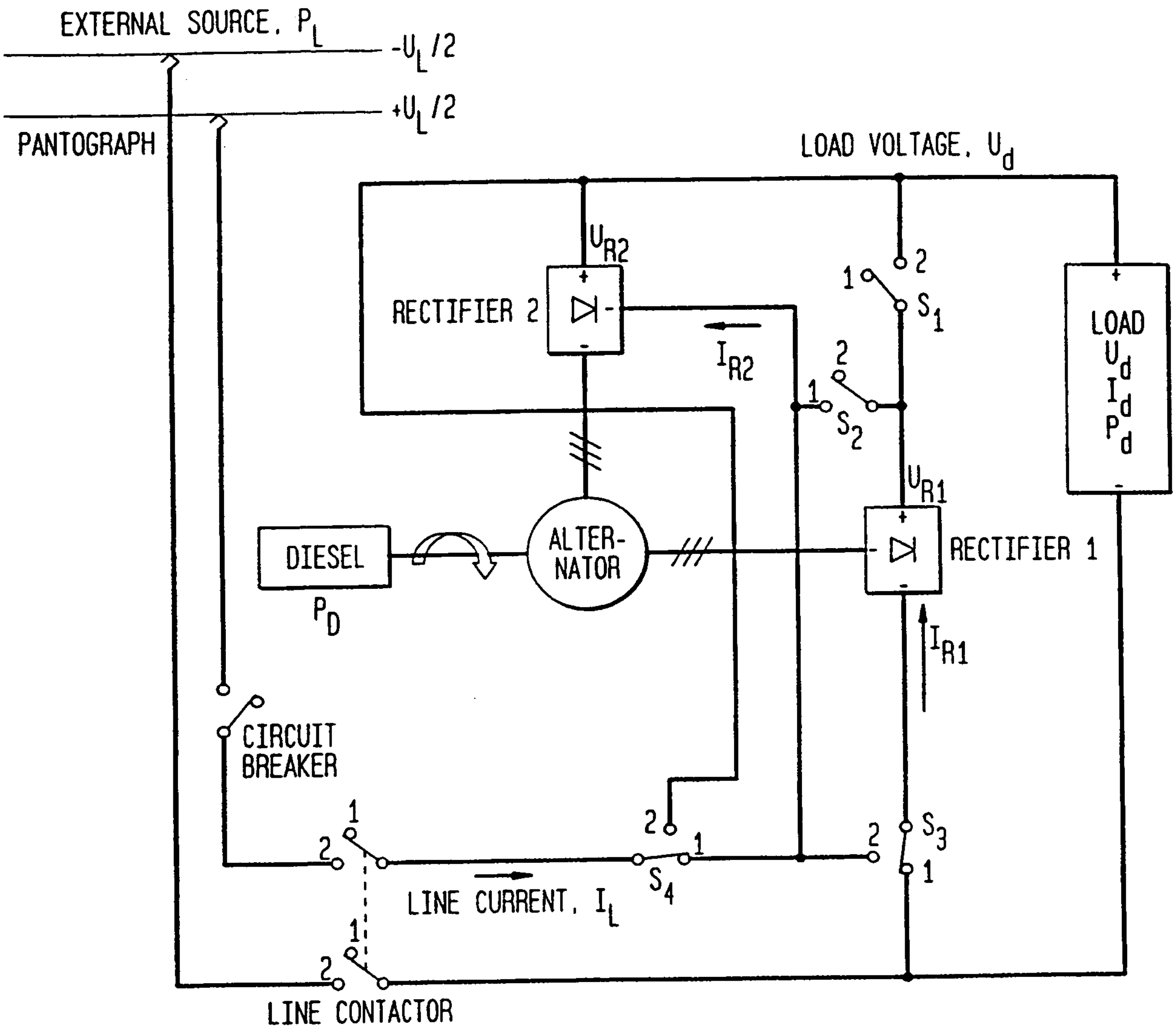

EXTERNAL SOURCE, P_L
$-U_L/2$
$+U_L/2$
PANTOGRAPH
LOAD VOLTAGE, U_d
U_{R2}
RECTIFIER 2
I_{R2}
S_1
S_2
U_{R1}
LOAD
U_d
I_d
P_d
DIESEL
P_D
ALTER-
NATOR
RECTIFIER 1
I_{R1}
CIRCUIT
BREAKER
S_3
S_4
LINE CURRENT, I_L
LINE CONTACTOR

FIG. 8

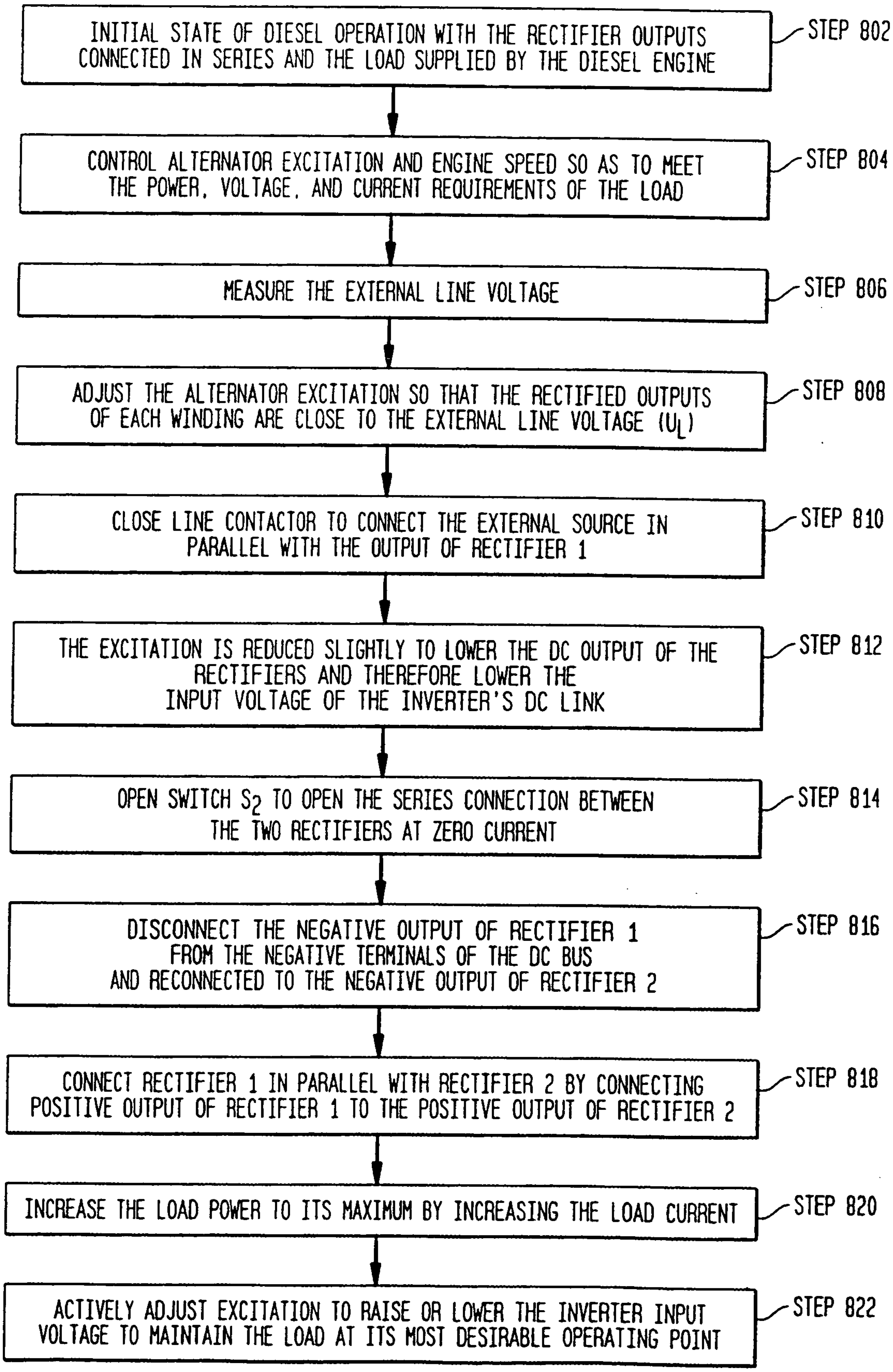

INITIAL STATE OF DIESEL OPERATION WITH THE RECTIFIER OUTPUTS CONNECTED IN SERIES AND THE LOAD SUPPLIED BY THE DIESEL ENGINE
STEP 802
CONTROL ALTERNATOR EXCITATION AND ENGINE SPEED SO AS TO MEET THE POWER, VOLTAGE, AND CURRENT REQUIREMENTS OF THE LOAD
STEP 804
MEASURE THE EXTERNAL LINE VOLTAGE
STEP 806
ADJUST THE ALTERNATOR EXCITATION SO THAT THE RECTIFIED OUTPUTS OF EACH WINDING ARE CLOSE TO THE EXTERNAL LINE VOLTAGE (U_L)
STEP 808
CLOSE LINE CONTACTOR TO CONNECT THE EXTERNAL SOURCE IN PARALLEL WITH THE OUTPUT OF RECTIFIER 1
STEP 810
THE EXCITATION IS REDUCED SLIGHTLY TO LOWER THE DC OUTPUT OF THE RECTIFIERS AND THEREFORE LOWER THE INPUT VOLTAGE OF THE INVERTER'S DC LINK
STEP 812
OPEN SWITCH S_2 TO OPEN THE SERIES CONNECTION BETWEEN THE TWO RECTIFIERS AT ZERO CURRENT
STEP 814
DISCONNECT THE NEGATIVE OUTPUT OF RECTIFIER 1 FROM THE NEGATIVE TERMINALS OF THE DC BUS AND RECONNECTED TO THE NEGATIVE OUTPUT OF RECTIFIER 2
STEP 816
CONNECT RECTIFIER 1 IN PARALLEL WITH RECTIFIER 2 BY CONNECTING POSITIVE OUTPUT OF RECTIFIER 1 TO THE POSITIVE OUTPUT OF RECTIFIER 2
STEP 818
INCREASE THE LOAD POWER TO ITS MAXIMUM BY INCREASING THE LOAD CURRENT
STEP 820
ACTIVELY ADJUST EXCITATION TO RAISE OR LOWER THE INVERTER INPUT VOLTAGE TO MAINTAIN THE LOAD AT ITS MOST DESIRABLE OPERATING POINT
STEP 822

FIG. 9

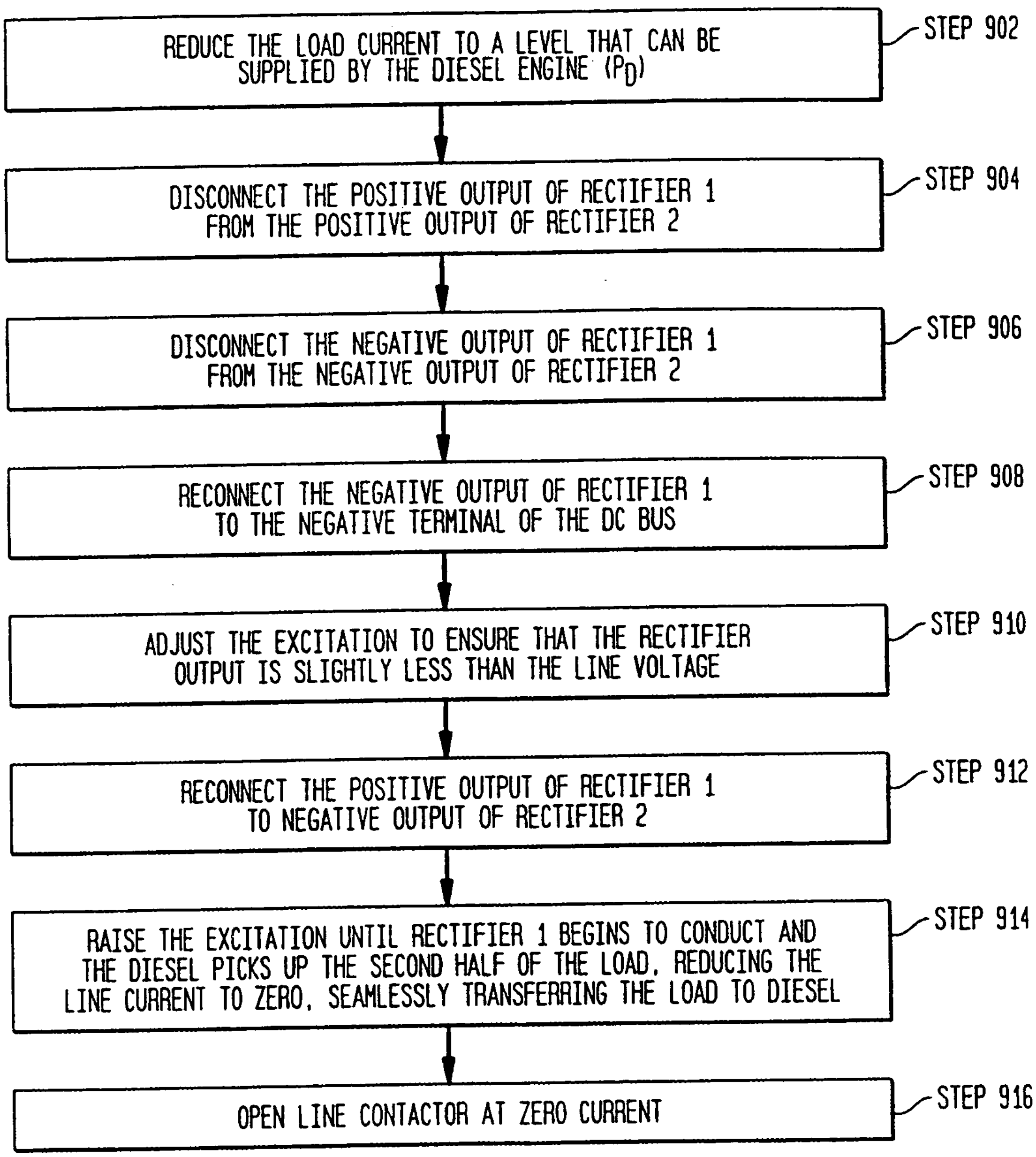
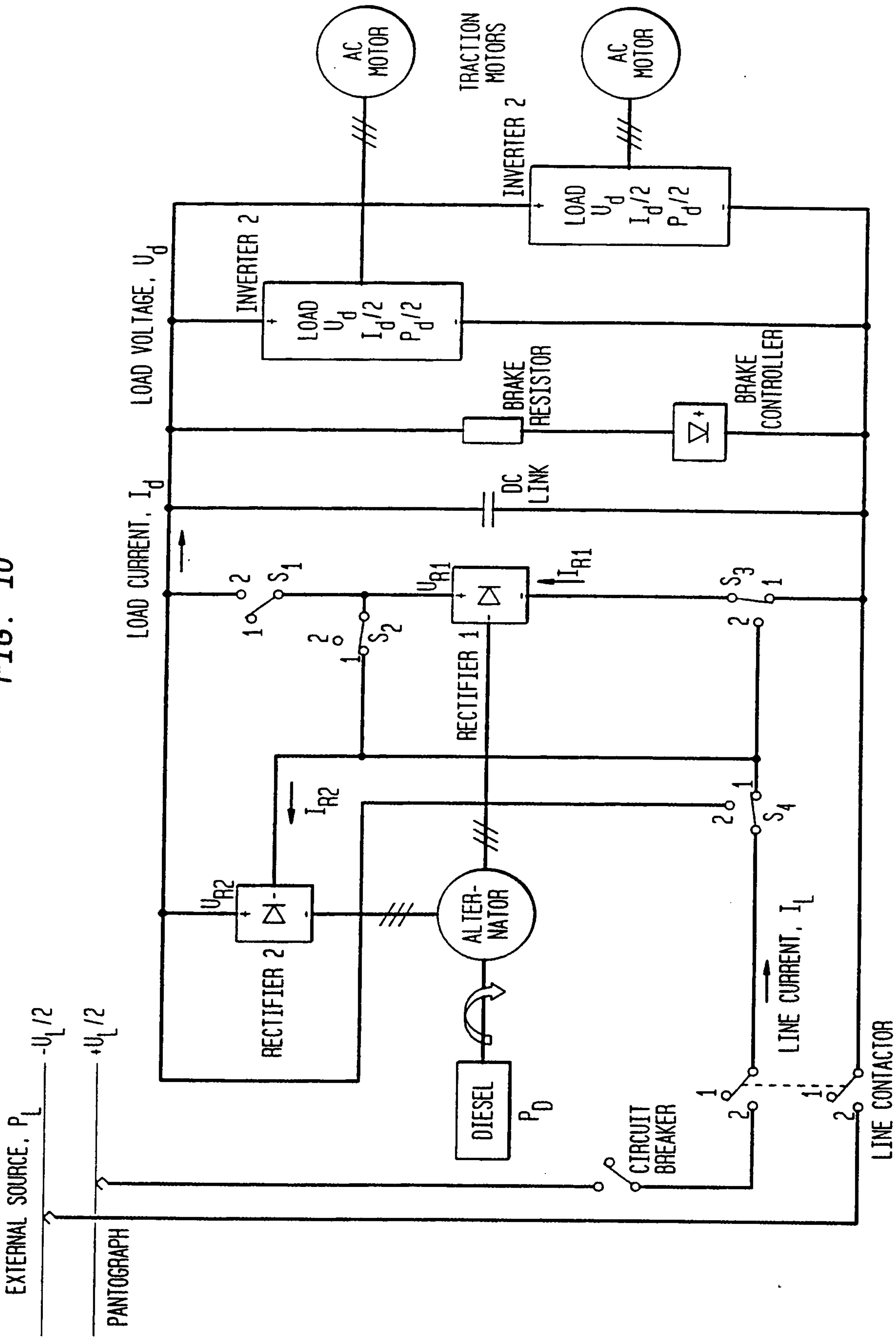

REDUCE THE LOAD CURRENT TO A LEVEL THAT CAN BE SUPPLIED BY THE DIESEL ENGINE (P_D)
STEP 902
DISCONNECT THE POSITIVE OUTPUT OF RECTIFIER 1 FROM THE POSITIVE OUTPUT OF RECTIFIER 2
STEP 904
DISCONNECT THE NEGATIVE OUTPUT OF RECTIFIER 1 FROM THE NEGATIVE OUTPUT OF RECTIFIER 2
STEP 906
RECONNECT THE NEGATIVE OUTPUT OF RECTIFIER 1 TO THE NEGATIVE TERMINAL OF THE DC BUS
STEP 908
ADJUST THE EXCITATION TO ENSURE THAT THE RECTIFIER OUTPUT IS SLIGHTLY LESS THAN THE LINE VOLTAGE
STEP 910
RECONNECT THE POSITIVE OUTPUT OF RECTIFIER 1 TO NEGATIVE OUTPUT OF RECTIFIER 2
STEP 912
RAISE THE EXCITATION UNTIL RECTIFIER 1 BEGINS TO CONDUCT AND THE DIESEL PICKS UP THE SECOND HALF OF THE LOAD, REDUCING THE LINE CURRENT TO ZERO, SEAMLESSLY TRANSFERRING THE LOAD TO DIESEL
STEP 914
OPEN LINE CONTACTOR AT ZERO CURRENT
STEP 916

FIG. 10



AC MOTOR
TRACTION MOTORS
AC MOTOR
INVERTER 2
INVERTER 2
LOAD U_d $I_d/2$ $P_d/2$
LOAD U_d $I_d/2$ $P_d/2$
LOAD VOLTAGE, U_d
BRAKE RESISTOR
BRAKE CONTROLLER
DC LINK
LOAD CURRENT, I_d
S_1
S_2
S_3
S_4
U_{R1}
I_{R1}
RECTIFIER 1
I_{R2}
U_{R2}
RECTIFIER 2
ALTER-NATOR
DIESEL
P_D
CIRCUIT BREAKER
LINE CURRENT, I_L
LINE CONTACTOR
EXTERNAL SOURCE, P_L
$-U_L/2$
$+U_L/2$
PANTOGRAPH

PCT

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International Bureau

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(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: BROWN, Gerald, Murray [–/US]; 450 Summerfield Drive, Alpharetta, GA 30022 (US).

(74) Agents: ASPERAS, I., Marc et al.; Siemens Corporation, Intellectual Property Dept., 186 Wood Avenue South, Iselin, NJ 08830 (US).

(81) Designated States: AU, BR, CA, CN, ID, IL, IN, JP, MX, SG, US, ZA, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

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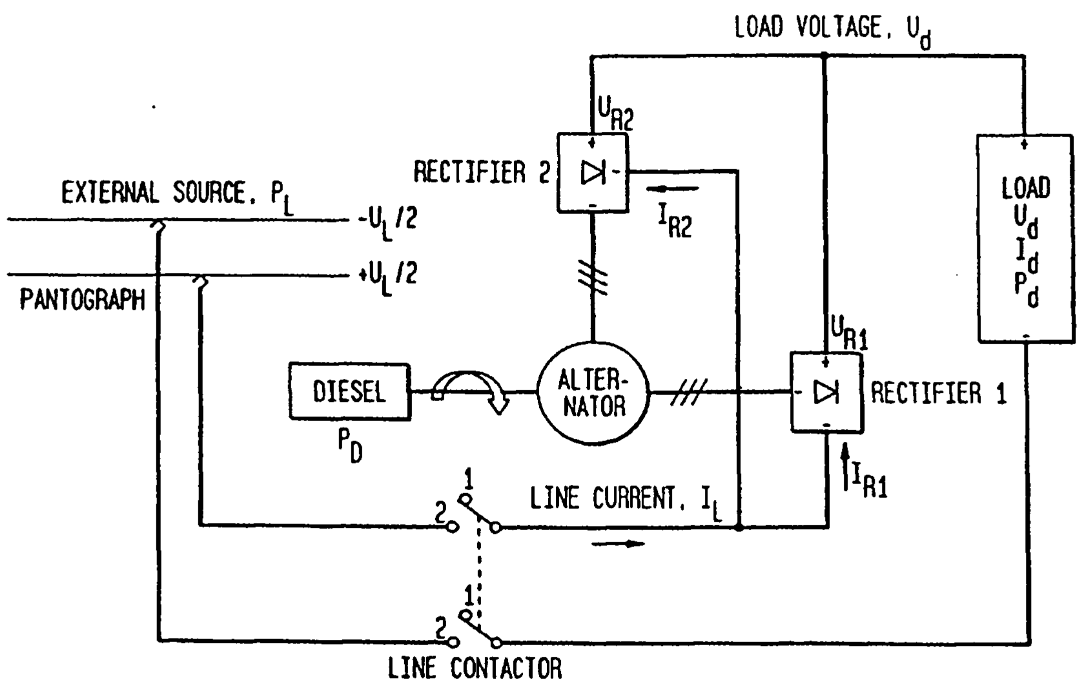
(54) Title: SYSTEM, METHOD AND APPARATUS FOR CONNECTING ELECTRICAL SOURCES IN SERIES UNDER FULL LOAD



(57) Abstract

A circuit connects a low–voltage high–current DC power source (P_L) in series with a high–voltage low–current DC source (P_D). The series connection is made under full power by using the second source P_L to commutate the load current and allow the first source P_D to be reconfigured from series to parallel operation, doubling its current rating.

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/30426

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B60L11/18 B60L15/20

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B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 B60L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 853 553 A (HOSIE ALAN P) 1 August 1989 (1989-08-01)	1,23
A	the whole document	2-22, 24-44
X	DE 196 28 877 A (BAYERISCHE MOTOREN WERKE AG) 22 January 1998 (1998-01-22)	1,23
A	claims 1,12	2-8, 24-30
A	WO 93 04887 A (WAGNER MINING & CONSTR) 18 March 1993 (1993-03-18) abstract; figure 4	1,17-21, 23,40-44
A	WO 82 00225 A (GEN ELECTRIC) 21 January 1982 (1982-01-21) abstract; figure 1	1,9,10, 23,31,32

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Date of the actual completion of the international search	Date of mailing of the international search report
10 April 2000	28.04.00

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PCT/US 99/30426

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
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WO 9304887	A	18-03-1993	US	5293947	A	15-03-1994
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			BR	8108668	A	25-05-1982
			DE	3170696	D	04-07-1985
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			IN	154216	A	06-10-1984
			MX	150409	A	30-04-1984
			ZA	8104609	A	23-02-1983
			CA	1172694	A	14-08-1984